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TITLE: Nanostructures: Physics and Technology International Symposium [6th] held in St. Petersburg, Russia on June 22-26, 1998 Proceedings

Delta-doping of GaAs by Sn

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Abstract. GaAs structures δ-doped by Sn with various densities of Sn have been grown and investigated. The Hall effect and Shubnikov–de Haas effect have been investigated for temperatures 0.4 K $< T <$ 12 K in magnetic fields up to 38 T. The maximum density of free electrons achieved was 8.3×10^{13} cm^{-2}. The resistance oscillations observed for a magnetic field parallel to the δ-layer were associated with singularities in the calculated density of states.

Introduction

Tin has been rarely used for δ-doping in GaAs because of its high segregation ability [1]. On the other hand, this donor impurity is less amphotere compared with silicon, which is usually used as dopant for δ-layers. The investigation of Tin δ-doping in GaAs on singular substrates is important for research on Tin δ-doping on vicinal substrates. These latter structures show a perspective for obtaining one-dimensional electronic channels [2, 3].

1 Samples

The GaAs(δ-Sn) structures were grown by molecular-beam epitaxy. On semi-insulating GaAs (Cr) substrate (001) a buffer layer of *i*-GaAs (240 nm) was grown. At a temperature of 450°C a tin layer was deposited in the presence of an arsenic flux. The structures were covered by a layer of *i*-GaAs (width 40 nm) and a contact layer *n*-GaAs (width 20 nm) with a concentration of silicon 1.5×10^{18} cm^{-3}. The design density of tin in the δ-layer smoothly varied from $N_D = 2.9 \times 10^{12}$ cm^{-2} in sample No. 1 up to $N_D = 2.5 \times 10^{14}$ cm^{-2} in sample No. 7.

2 Results

The temperature dependence of the resistance of samples No. 1 up to No. 7 is shown in Fig. 1a. The Hall effect and the magnetoresistance were measured at temperatures 0.4 K $< T <$ 12 K in magnetic fields up to 10 T and pulsed fields up to 38 T. The obtained values of the Hall concentration n_H and the Hall mobility μ_H at $T = 4.2$ K are shown in Table 1. The concentration of free electrons in the tin-doped structures does not saturate as function of design doping density, as was observed in Si δ-doped structures [4].

In magnetic fields $B < 0.2$ T at low temperatures a negative magnetoresistance was observed for all samples. In strong magnetic fields the Shubnikov–de Haas effect

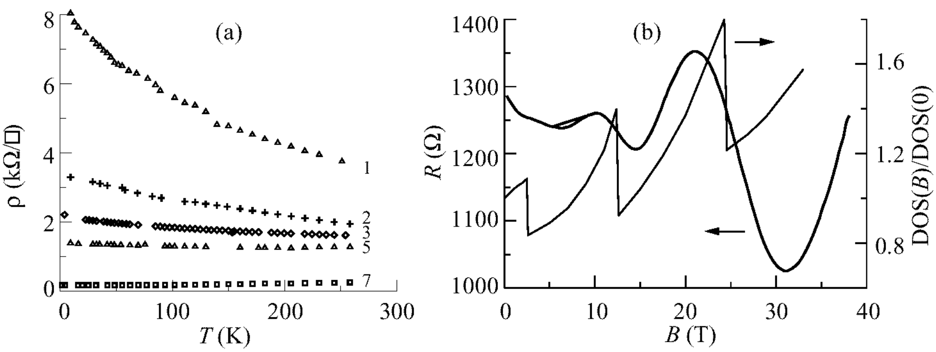

Fig 1. a) Temperature dependence of the sheet resistivity for different samples. b) Experimental dependence of the resistance on parallel magnetic field and the calculated DOS at the Fermi energy for sample No. 6.

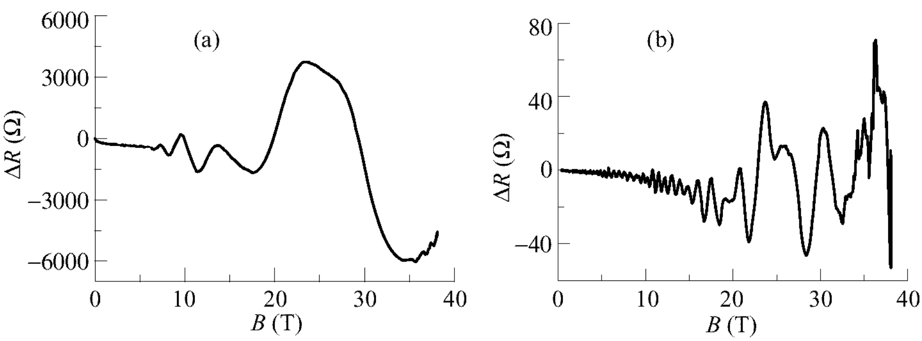

Fig 2. Oscillating part of the magnetoresistance for sample No. 6 (a) and No. 7 (b).

was observed at $T = 4.2$ K in the investigated structures (Fig. 2 and 3). The angular dependence of the oscillation frequency revealed, that the oscillations were caused by two-dimensional carriers. The electron concentrations of the subbands, determined from the maxima in the Fourier spectra, and the electron quantum mobilities, obtained from the width of the peaks in the Fourier spectra, are shown in Table 2.

Table 1. Hall density n_H, sum of the Shubnikov–de Haas concentrations n_{SdH} in all subband and Hall mobility μ_{H} at temperature $T = 4.2$ K for samples No. 1–7.

Sample No.	n_{H} (10^{12} cm^{-2})	Σn_{SdH} (10^{12} cm^{-2})	μ_{H} (cm^2/Vs)
1	1.74	2.75	1530
2	3.23	1.04	540
3	2.63	2.03	1080
4	10.4	6.15	1200
5	8.35	8.09	1150
6	14.5	8.73	1940
7	83.5	45.3	1170

Table 2. The electron concentration n_{SdH} and the quantum mobility μ_q^{SdH} obtained from the Shubnikov–de Haas effect at $T = 4.2$ K; the self-consistently calculated concentration N_S; the calculated quantum mobility μ_q^t of electrons due to multi-subband scattering on ionized impurities; experimentally determined $B_{\|}$ and calculated depopulation magnetic field $B_{\|}^t$ for samples No. 1 and No. 6.

Sample No.	i subbands No.	n_{SdH} (10^{12} cm^{-2})	N_S (10^{12} cm^{-2})	μ_q^{SdH} (cm^2/Vs)	μ_q^t (cm^2/Vs)	$B_{\|}$ (T)	$B_{\|}^t$ (T)
	0	1.76	1.75	1340	1570	–	–
1	1	0.99	0.99	1450	1590	18.6	22.5
	2	–	0.30	–	2940	4	8.0
	0	4.08	4.02	860	1290	–	–
	1	2.33	2.80	1660	1450	–	45.3
6	2	1.56	1.59	2120	2380	25.8	24.5
	3	0.76	0.67	3000	4460	12.6	12.5
	4	–	0.06	–	3530	4.4	3.0

3 Discussion

The band diagrams, wave functions and electron concentration in each subbands were calculated by solving self-consistently Schrödinger and Poisson equations [5]. Non parabolicity of the conduction band in the Γ point and the exchange-correlation contribution to the electrostatic potential were included. The width of the δ-layer of ionized impurities, used in the calculations as a adjustable parameter, was approximately equal to 16 nm for all samples. Such a width for a δ-layer is bigger than in Si δ-doped structures [4], but is rather small for Tin [1].

The electron quantum mobilities due to multi-subband scattering on ionized impurities [5, 6] were calculated. The screening of the Coulomb scattering potential was taken into account within the random-phase approximation [6]. The calculated mobilities are in reasonable agreement with our experimental results (see Table 2).

In sample No. 7 with the highest electron concentration the conductance band in the L point is filled by electrons at low temperatures (according to Ref. [4] this occurs at a concentration of ionized impurity greater than $N_D = 1.6 \times 10^{13}$ cm^{-2}). If the highest frequency in the Fourier spectrum (Fig. 3b) corresponds to the lower subband $i = 0$ in the Γ point with concentration 9.75×10^{12} cm^{-2}, then, according to our calculations, two subbands should be filled in the L point with concentration 3.7×10^{13} cm^{-2} and 2.0×10^{13} cm^{-2} (the corresponding frequencies are designated by asterisks in Fig. 3b). This is the first experimental observation of such a high concentration of electrons in δ-doped GaAs structures, at which a conductance band at the L point is populated at helium temperatures.

The measurement of magnetoresistance in magnetic field parallel to the δ-layer allows one to determine accurately the number of occupied subbands [7]. For the magnetic field B directed along the y-axis and the vector potential equal to $\mathbf{A} = (Bz,0,0)$, the

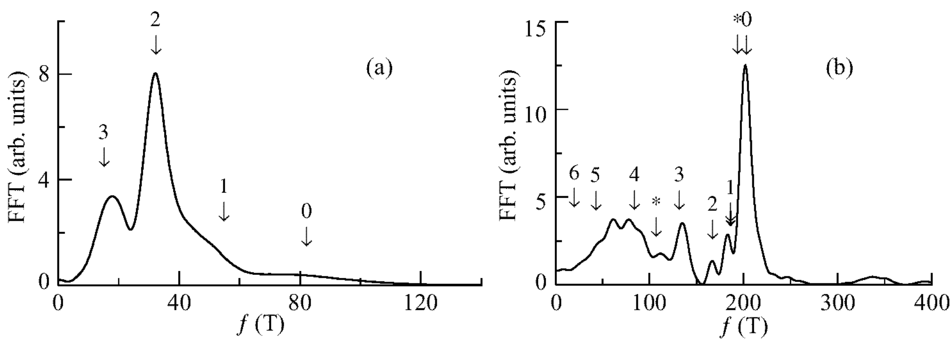

Fig 3. Fourier spectrum of the Shubnikov–de Haas oscillations for sample No. 6 (a) and No. 7 (b). Arrows correspond to calculated subbands in the Γ point. Asterisks correspond to calculated subbands in the L point.

Schrödinger equations reads:

$$\left[\frac{p_y^2}{2m^*} + \frac{1}{2m^*}\left(p_x + ezB\right)^2 - \frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2} + \Phi(z)\right]\Psi = E\Psi,$$

where the potential $\Phi(z)$ is a sum of an electrostatic potential, determined from the Poisson equation, and the exchange-correlation potential. The total density of states (DOS) at the Fermi level increases with increasing magnetic field and drops after the subband level has crossed the Fermi level (Fig. 1b).

The work was supported by the Russian Foundation for Basic Research (Grant No. 97-02-17396) and by the Dutch organizations N.W.O. and F.O.M.

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